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ST. LAWRENCE RIVER FREEZE-UP FORECAST PROCEDURE

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CONTENTS

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A standard operating procedure (SOP) is presented for calculating the date of freeze-up on the St. Lawrence River at Massena, N.Y. The SOP is based on two empirical tempera.-ture decline equations developed far Kingston, Ont., and Massena, N.P., respectively. Input data needed to forecast freeze-up consist of the forecast December flow rate and heat flux for the St. Lawrence River and the water temperature at Kingston, Ont., on the forecast initiation date. Forecasts are made October 1, October 15, November 1, November 15, December 1, and December 15.

1. INTRODUCTION

A forecast technique to predict freeze-up on the St. Lawrence River at Massena, N.Y., was developed by the Great Lakes Environmental Research Laboratory as part of the Demonstration Program to Extend the Navigation Season on the Great Lakes and St. Lawrence Seaway. Figure 1 portrays the area of the St. Lawrence River used in the development of the forecast and the specific area for which the forecast is made. The forecast technique has been in the development and test phase for the past 3 years. The purpose of this memorandum is. to present a standard operating procedure (SOP) to be used in making operational freeze-up forecasts. The reader is referred to an article by Adams (1976) for a complete discussion of forecast technique development. In instances where Adams's forecast technique was modified for use in the present SOP, the modifications are noted here.

2. FORECAST EQUATIONS

The freeze-up forecast is based upon two temperature decline equations. Equation (1) is as follows:

$$T_1 = T_0 + \frac{Q_t F}{983}, \tag{1}$$

where T_1 is the water temperature at Massena, N.Y., T_0 is the water temperature at Kingston, Ont., one travel time earlier, and Q_t is the given average river surface heat flux rate between Kingston and Massena. All temperatures are in °C. (The travel time, F, is the time in days needed for a unit volume of water to travel from Kingston to Massena.) The river is assumed to be well mixed and isothermal during the forecast period (October, November, and December). Freeze-up at Massena is defined as the time when the water temperature at Massena is predicted to be 0.3°C, i.e., when $T_1 = 0.3°C$. At that time, it is probable that an ice cover has formed from shore to shore in the forecast area. It should be noted that, although the ice cover

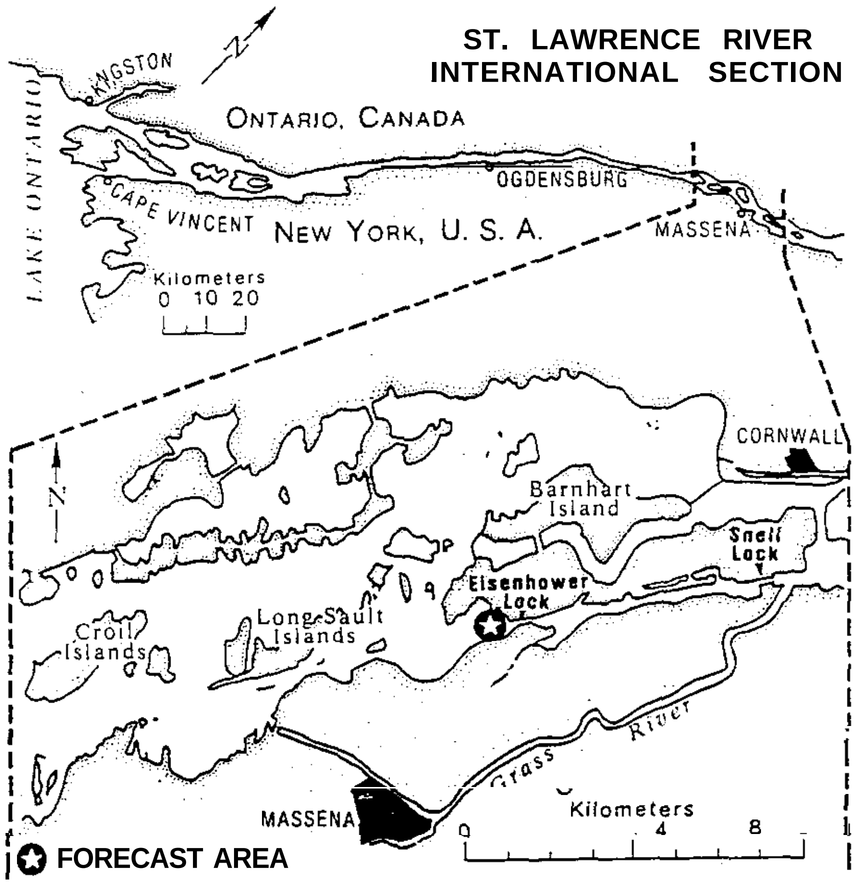

Figure 1. Area of the St. Lawrence River used in the development of the forecast.

may be lost after the initial freeze-up (due to mild weather), it is the initial freeze-up of the winter season that is forecast by the SOP. Setting T_1 in equation (1) equal to 0.3°C and solving for T_0, the water temperature at Kingston one travel time earlier, results in the following expression:

$$T_0 = 0.3 - \frac{Q_t F}{983} \qquad (1a)$$

By the use of equation (1a), T_0, the water temperature at Kingston one travel time before freeze-up at Massena, can be calculated if Q_t and F are known. Methods of estimating Q_t and F are given in Section 3 below.

Equation (2) is then used to estimate the time needed for the water at Kingston to cool from T_i the temperature on the date the forecast is initiated to T_0.

$$\Delta T = (aT - b)t^c, \tag{2}$$

where ΔT is the temperature difference at Kingston from the date the forecast is made to one travel time prior to freeze-up at Massena (i.e., $T - T_0$); t is the time in days for the water temperature to drop from T to T_0; and a, b, and c are constants dependent on the forecast start date. Solving equation (2) for t and putting it in logarithmic form to facilitate computation results in equation (2a) below:

$$\log t = 1/c\ [\log (T - T_0) - \log (aT - b)]. \tag{2a}$$

The number of days, N, from the date of the forecast to the forecasted date of freeze-up at Massena is then easily calculated by equation (3),

$$N = t + F, \tag{3}$$

where t is the time in days for the water at Kingston to cool from T to T_0 and F is the time needed for the water to travel from Kingston to Massena.

3. FORECAST INPUT

Input parameter* needed for the solution of equations (la), (2a), and (3) are T, F, and Q_t. The value of T, the daily average water temperature at Kingston, is obtained from the Kingston water purification plant. It should be noted that the location of the water temperature sensor at Kingston was changed from 1000 ft off shore in 50 ft of water to 2800 ft off shore in 58 ft of water in the summer of 1970. Freeze-up forecast* the past 3 years indicate the change in location does not appear to have significantly changed forecast accuracy (Appendix B).

The value of F, the travel time, is calculated from the mean December forecast flow rate of the river obtained from the U.S. Army Corps of Engineers, Detroit District. The value of Q_t is calculated from regression equations of Q_t and T. The values of Q_t used to derive the regression equations, unlike those in Adams's report (1975), which are based on heat budget analysis of climatological data, are based on solution of the forecast equations working backward from the actual freeze-up date and F and T values.

4. FORECAST STANDARD OPERATING PROCEDURE (SOP)

4.1 Initial Forecast and Update*

The October 1 forecast of freeze-up is usually made October 2 as input values must be known for the forecast date. The forecast will be updated on October 15, November 1, November 15, December 1, and December 15. If on any of these dates input data are not available, the forecast will be made on the first date when input data for the forecast date are available.

4.2 Forecast Procedure

1. Call the water purification plant at Kingston to obtain daily average water temperature for the date on which the forecast is made (T).

2. Call the U.S. Army Corps of Engineers, Detroit District, to obtain the forecast December flow rate for the St. Lawrence River.

3. Calculate travel time (F) from the following formula:

$$F = \frac{2.1303 \times 10^6 \text{ days}}{\text{December flow rate}} \quad (4)$$

where the December flow rate is given in cubic feet per second.

4. Calculate the value of Q_t, the December heat flux rate, from one of the following equations:

   A. October 1 forecast $Q_t = 113.6 - 28.7T$ (5)

   E. October 15 forecast $Q_t = 202.6 - 38.7T$ (6)

   C. November 1 forecast $Q_t = 120.1 - 42.4T$ (7)

   D. November 15 forecast $Q_t = -102.8 - 26.9T$ (8)

   E. December 1 forecast $Q_t = -50.7 - 48.5T$ (9)

   F. December 15 forecast $Q_t = 38.1 - 97.6T$. (10)

5. Calculate the value of T_0 from equation (la),

$$T_0 = 0.3 - \frac{Q_t \times F}{983},$$

where T_0 is the water temperature at Kingston one travel time before freeze-up occurs at Massena.

6. Calculate the value of t from equation (2a),

$$\log t = l/c\ [\log (T - T_0 - \log (aT - b)],$$

where T is given from step 1 above and T_0 is calculated from step 5. The values of a; b, and c will depend on the date the forecast is made as follows:

To be used with:	a	b	c
A. October 1 forecast	0.00935	0.04920	1.09886
B. October 15 forecast	0.01055	0.04061	1.09886
C. November 1 forecast	0.01750	0.09200	1.09886
D. November 15 forecast	0.02727	0.12952	1.09886
E. December 1 forecast	0.05180	0.21750	1.09886
F. December 15 forecast	0.01617	-0.02665	1.09886.

7. The predicted freeze-up date is then calculated from equation (3),

$$N = t + F ,$$

where t is as calculated from step 6, and F is as calculated from step 3. This is a modification from Adams (1976) in which a slightly different accounting procedure was used, but the results are virtually the same when the forecast freeze-w date is converted to a Julian date. To convert these data to the Julian date, use the appropriate conversion factor given below:

A. October 1 forecast	274 + N
B. October 15 forecast	288 + N
C. November 1 forecast	305 + N
D. November 15 forecast	319 + N
E. December 1 forecast	335 + N
F. December 15 forecast	349 + N.

On leap years add 1 day to the dates predicted.

4.3 Sample Calculation

Suppose the following input data (i.e., 1 and 2 below) were obtained for the October 1, 1974, forecast:

(1) T is 16.1°C

(2) Forecast December flow is 269,000 ft^3/s

(3) Solving for F in equation (4),

$$F = \frac{2.1303 \times 10^6}{2.69 \times 10^{'}} \text{ days} = 7.9 \text{ days}$$

(4) Solving equation (5) for Q_t for October 1,

$$Q_t(\text{Oct } 1) = 113.6 - 28.7\ T = 113.6 - [(28.7) \times (16.1)] = -348$$

(5) Solving equation (la) for T_0,

$$T_0 = 0.3 - \frac{Q_t F}{983} = 0.3 - \frac{(-348 \times 7.9)}{983} = 3\ 1^\circ C$$

(6) Solving equation (2a) for log t,

$$\log t = 1/c\ [\log (T - T_0) - \log (aT - b)].$$

For October 1 a = 0.00935

b = 0.04920

c = 1.09886

Therefore $\log t = \frac{1}{1\ 09886} [\log (16.1 - 3.1) - \log (0.00935 \times 16.1 - 0.0492)]$

$$\log t = \frac{1}{1\ 09886} [\log (13.0) - \log (0.101335)]$$

$$\log t = 0.910034\ [(1.113943) - (-0.994241)]$$

$$\log t = 1.9185.$$

(7) Solving equation (3),

$$N = t + F = 82.9 + 7.9 = 90.8.$$

To convert this number to the Julian date, choose the appropriate equation (in this case the October 1 forecast),

$$274 + N = 274 + 90.8 = 364.8.$$

Therefore the predicted freeze-up date is December 30.8.

4.4 Interpretation of Predicted Freeze-Up Date

Whether this freeze-up date of December 30.8 should be rounded to December 31 or truncated at December 30 will be left to the discretion of the forecastor as no criteria exist for rounding up or down.

The most important thing to keep in mind is that the SOP is an *analytical* tool which must be employed with common sense and imagination and in conjunction with as many other forecast aids as are available. For example, given an October 1 water temperature of 19.0°C (an alltime highj and a projected December travel time of 10.0 days, the method would predict an abnormally early freeze-up on December 22.9. This is so primarily because the December heat flux rate is directly proportional to the starting temperature. If, however, the National Weather Service was calling for above normal temperatures in their long-range forecast for the autumn cooling period, it would be foolish to adhere blindly to the results of the forecast technique alone.

5. REFERENCE

Adams, C. E. 1976. Estimating water temperatures and the time of ice on the St. Lawrence River. *Journal of Limnology and Oceanography* 21(1).

6. ACKNOWLEDGMENTS

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APPENDIX A. FLOW-RATE TRAVEL TIME

The relationship between forecast December flow rates for the St. Lawrence River and the time needed for a mass of water to travel from Kingston to Massena is expressed by the following formula:

$$F = \frac{2.1303 \times 10^6}{\text{flow rate}},$$

where F = the travel time in days and flow rates are given in thousands of cubic feet per second. The equation was derived from averages of St. Lawrence Seaway cross-sectional areas, volume flow rate, and distance traveled and is as follows.

$$F = \frac{\text{Area (ft}^2\text{) distance (ft)}}{\text{flow rate (ft}^3\text{/s)}} = \text{seconds} \cdot \frac{\text{day}}{8.64 \times 10^4 \text{ s}} = \text{days.}$$

APPENDIX B. EVALUATION

Evaluations of freeze-up date forecasts for 9 of the past 10 winters by use of the SOP were made (table B.2). Note that the lowest standard error of estimate (SE) occurred for the November forecasts. The reason for this is not apparent.

Table B.l. Temperatures at Kingston (°C)

DATE	OCT. 1	OCT. 15	NOV. 1	NOV. 15	DEC. 1	DEC. 15	JAN. 1	Travel Time in Days F
1965-66	15.6	12.2	10.0	7.2	5.6	4.4	3.3	9.4
1966-67	14.4	12.8	11.1	9.4	7.8	6.1	3.3	9.8
1967-68	15.0	13.3	11.1	9.4	5.6	3.9	2.8	7.6
1968-69	17.8	15.0	12.8	9.4	6.7	3.9	1.9	8.4
1969-70	16.7	15.0	11.1	10.0	6.1	4.4	1.1	8.8
1970-71	17.8	17.2	13.3	11.1	7.2	4.4	2.2	8.2
1972-73	16.7	13.9	10.6	8.3	6.1	2.8	1.1	7.9
1973-74	17.5	16.1	12.0	8.3	6.7	4.7	2.2	8.0
1974-75	16.1	13.3	11.7	8.9	6.4	4.4	3.3	7.6

Table B.2. Forecast of Freeze-Up Dates as Mode on Various Forecast Initiation Dates

Year	FORECAST INITIATION DATES Oct. 1	Oct. 15	Nov. 1	Nov. 15	Dec. 1	Dec. 15	Observed Freeze-Up Date
1965-66	Dec. 30.5	Jan. 2.0	Jan. 4.5	Jan. 5.4	Jan. 1.9	Dec. 27.7	Jan. 9
1966-67	Jan. 2.8	Dec. 30.8	Dec. 29.5	Dec. 25.9	Dec. 24.2	Dec. 26.6	Dec. 26
1967-68	Jan. 3.2	Dec. 31.4	Jan. 1.0	Dec. 27.8	Jan. 5.4	Dec. 31.2	Jan. 2
1968-69	Dec. 26.6	Dec. 27.0	Dec. 25.5	Dec. 27.1	Dec. 27.8	Dec. 29.7	Dec. 25
1969-70	Dec. 28.5	Dec. 26.6	Dec. 30.6	Dec. 25.4	Dec. 30.1	Dec. 29.0	Dec. 28
1970-71	Dec. 26.8	Dec. 23.8	Dec. 24.5	Dec. 23.9	Dec. 26.5	Dec. 30.2	Dec. 24
1972-73	Dec. 29.4	Dec. 29.7	Jan. 3.0	Dec. 31.6	Dec. 31.4	Dec. 29.9	Dec. 30
1973-74	Dec. 27.6	Dec. 25.5	Dec. 28.5	Dec. 31.5	Dec. 28.3	Dec. 30.8	Dec. 30
1974-75	Dec. 31.1	Dec. 31.4	Dec. 29.7	Dec. 29.4	Dec. 30.0	Dec. 31.5	Jan. 1
SE	4.60	3.55	2.86	2.80	3.43	5.23	4.92